Sun and dust versus greenhouse gases: an assessment of their relative roles in global climate change

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Many mechanisms, including variations in solar radiation and atmospheric aerosol concentrations, compete with anthropogenic greenhouse gases as causes of global climate change. Comparisons of available data show that solar variability will not counteract greenhouse warming and that future observations will need to be made to quantify the role of tropospheric aerosols, for example.

OBSERVATIONS of steadily increasing concentrations, principally man-made, of greenhouse gases in the Earth's atmosphere[1-3] have led to the expectation of global warming during coming decades[4-6]. Computer simulations, supported by palaeoclimate studies, suggest that the potential greenhouse climate change within a century could rival the difference between today's climate and the last great ice age of 20,000 years ago[7,8]. But the greenhouse effect is in competition with other mechanisms for climate change. Solar variability, although a speculative subject, has received much attention, and recent observational advances allow initial quantitative comparison of the effects of the Sun and the greenhouse. Another mechanism, a change in the atmospheric aerosols (natural and man-made), is of comparable importance.

Because curtailing the growth of greenhouse gases would require significant changes in global energy use and unprecedented international cooperation, it is essential to develop a good quantitative understanding of the relative importance of these different mechanisms of climate change. We also need to know how the magnitudes of such forced climate changes compare with unforced internal fluctuations of the climate system. Here we compare the above climate forcings, describe observations that would help sort out cause and effect of near-term global climate trends, and discuss implications for policy making.

Global climate can fluctuate without any change in the external forcing. For example, the Earth's simulated mean surface temperature varies as much as 0.4 °C in a 100-year run of a global climate model[9] with fixed solar irradiance and fixed greenhouse gases (Fig. 1). These fluctuations arise because the coupled nonlinear equations describing atmospheric structure and motion have solutions exhibiting chaotic behaviour. Tiny perturbations or changes of initial conditions (the flap of a butterfly's wings) give rise to solutions that are different on the timescale of months or years, and these fluctuations are magnified on decadal timescales as a result of the thermal inertia of the ocean, even if possible changes of ocean circulation are ignored[10,11]. In effect, the atmosphere and ocean do a lot of 'sloshing' around. Some of the sloshing, for example, the El Niño/Southern Oscillation phenomena[12], will eventually be predictable on a limited timescale, but most of it is of a chaotic nature for which long-term prediction is only possible in a statistical sense. An externally forced climate change must be at least comparable in magnitude to this internal noise to be clearly discernable.

A climate forcing, natural or anthropogenic, is an imposed change that modifies the planetary radiation balance, thus affecting the planetary temperature. The natural forcings that seem to be most significant, based on systematic comparison of radiative effects, are changes of stratospheric aerosols owing to large volcanic eruptions and changes of solar irradiance. The largest anthropogenic forcings seem to be increasing infrared-absorbing (greenhouse) gases, man-made tropospheric aerosols, and perhaps changes of surface reflectivity owing to desertification and deforestation.

The climate change that results from a change in the climate forcing depends on many feedback processes in the climate system. These feedbacks, including changes of clouds, water vapour, ice and snow cover, are complex and not well understood. Thus, climate sensitivity is very uncertain; for example, it is estimated that doubling the concentration of CO_2 in the atmosphere could lead to an eventual global warming anywhere in the range 1.5–5.5 °C[4,8,13,14]. Fortunately, this uncertainty can be largely avoided by contrasting the magnitude and timescale of the climate forcings rather than the resulting climate response. High-frequency changes in the forcing have less impact than a sustained forcing, because of the thermal inertia of the climate system. But uncertainties about ocean mixing rates, and thus about the effective thermal inertia of the system, only provide further reasons to focus first on climate forcing, and then discuss climate response.

Comparison of solar and greenhouse effects

A change of solar irradiance is perhaps the simplest climate forcing, and it serves as a standard for comparison. At the Earth's mean distance from the Sun, the irradiance normal to the Earth–Sun line is ~1,370 W m^{-2}. Because the Earth's surface area is four times its cross-section and 30% of the sunlight is reflected back to space without being absorbed, the mean solar heating of the Earth is ~240 W m^{-2}. A change of solar irradiance by 0.1% is therefore a climate forcing of ~0.24 W m^{-2}.

Greenhouse and solar climate forcings of recent years can be compared accurately. Precise measurements of CO_2, the

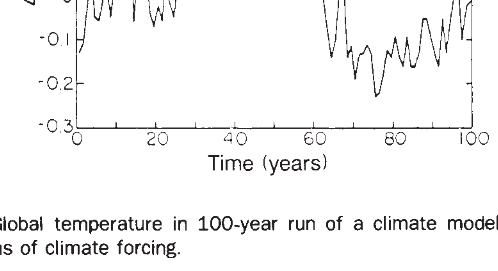

FIG. 1 Global temperature in 100-year run of a climate model[9] with no variations of climate forcing.

principal anthropogenic greenhouse gas, were initiated in 1958[1]. Since then, CO_2 has increased from 315 p.p.m. to over 350 p.p.m. The history of chlorofluorocarbons (CFCs) is also known[15], because CFCs are entirely man-made and production records are available. The trends of methane (CH_4) and nitrous oxide (N_2O), which contribute much less than CO_2 and CFCs to the greenhouse forcing over the past 30 years[15], are known approximately[16]. Ozone (O_3) , another greenhouse gas, is believed to be decreasing in the stratosphere and increasing in much of the troposphere, but the changes are so variable and poorly measured that it is impossible to say whether they cause a net global warming or cooling[15,17]. It is unlikely, however, that the ozone global climate forcing is >10–20% of the net forcing by the other gases.

The net climate forcing by CO_2, CFCs, CH_4 and N_2O for the period 1958–1989 is $>1\ \mathrm{W\,m^{-2}}$ (Fig. 2). This is the heating of the Earth's troposphere calculated with a simple (one-dimensional radiative-convective[5]) or a more sophisticated (three-dimensional[9]) climate model for the indicated changes of these gases. We calculated an increased greenhouse forcing between 1850 and 1989 (Fig. 2) of $\sim 2\ \mathrm{W\,m^{-2}}$. Others[16,18] have reported anthropogenic greenhouse forcing as large as $2.5\ \mathrm{W\,m^{-2}}$, the difference being due mainly to small increases of CO_2 and CH_4 before 1850, stratospheric H_2O (which chemical models suggest may have increased because of added CH_4) and uncertain O_3 changes. We have omitted any forcing owing to O_3 or stratospheric H_2O changes because even the sign of the O_3 forcing is uncertain and there are no confirming observations of long-term stratospheric H_2O changes. The 2–2.5 $\mathrm{W\,m^{-2}}$ greenhouse forcing is uncertain by a further 10–20% owing to imprecisions in the radiative parameters[6,19]. Our calculated history for the greenhouse climate forcing since 1958 is shown as the solid curve in Fig. 3.

Precise measurements of solar irradiance, obtained above the interfering effects of the Earth's atmosphere, were initiated in the late 1970s. A cavity radiometer[20] on the Nimbus 7 spacecraft has obtained data from late 1978 to the present, and an active-cavity radiometer[21] on the Solar Maximum satellite with more sophisticated calibrations obtained data from late 1979 through mid-1989. These instruments are believed to be capable of precisions (relative accuracies) of better than 0.1%. Despite some differences in results of the two instruments, they are consistent in showing a decline of solar irradiance of ~0.1% between 1979 and the mid 1980s, with a partial recovery of the irradiance by 1989.

Solar forcing of the climate system based on the present official Nimbus 7 data[20] is shown in Fig. 3, with zero forcing defined as the mean for the period of measurement. The combined greenhouse and solar forcing is also shown. Over the common period of accurate solar and greenhouse data the changing Sun significantly modulated the net climate forcing, but it did not alter the trend.

We stress that climate response to a given forcing depends on the history of that forcing over a period comparable to the response time of the climate system[8,10]. The response time is of the order of decades, and may be a century or more if climate sensitivity is high[8,22–24]. Because of this damping, the climate impact of a fluctuating forcing, such as the solar change in Fig. 3, is much less than that of a steady forcing. But solar irradiance may have long-term, as well as short-term, variations.

We also note that the climate system would not be expected to respond in exactly the same way to a change of solar forcing as it would to a change of greenhouse forcing of the same magnitude and timing. Solar heating, for example, is concentrated toward low latitudes, whereas greenhouse heating is more uniformly distributed; also, because solar variability is greatest at ultraviolet wavelengths[25], a substantial fraction of the change of absorbed solar energy occurs high in the atmosphere where it is less effective in warming the surface. Tests with global climate models[8,26] do, however, yield remarkably similar responses for doubled atmospheric CO_2 and for a (spectrally uniform) 2% increase of solar irradiance, both forcings being in the range 4–4.8 $\mathrm{W\,m^{-2}}$. Thus a comparison of solar and greenhouse forcings, as in Fig. 3, seems to be meaningful to first order.

The changes of solar irradiance in the past decade are associated with changes in the area of sunspots, which are dark cool regions of reduced irradiance, and faculae, which are bright regions of increased irradiance[27,28]. The faculae effect dominates, and thus the irradiance increases in periods of maximum solar activity. If the empirical relationships between the areas of sunspots and faculae and the solar irradiance deduced from the data of past decade were valid on all timescales, longer-term changes of solar irradiance would hardly exceed 0.1%. Nor are large fluctuations of energy flow from the solar interior expected: even if the rate of nuclear energy production varied, the long diffusion time for a photon to reach the solar surface, $\sim 10^4$ years, would smooth out the variations[29]. But changes in the efficiency of convection in the outer convective layers of the Sun, caused, for example, by fluctuations in magnetic field strengths, can alter the rates of energy storage and release. Given the magnitude of surface-layer energy reservoirs, this implies that there may be important changes in the solar irradiance on timescales from decades to centuries[29].

Indeed, Eddy[30] has argued that reduced solar irradiance during the Maunder minimum of solar activity (1640–1720) may have been responsible for the Little Ice Age when global temperature is estimated to have been as much as 1 °C colder than today[31]. Other possible causes for that climate change exist, including fluctuations of ocean heat transport and the increase

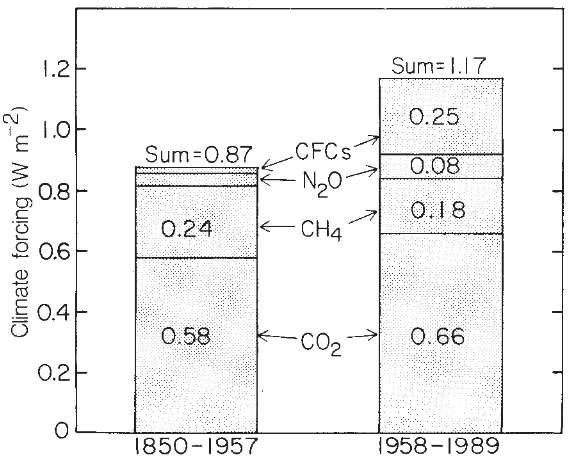

FIG. 2 Added greenhouse climate forcings ($\mathrm{W\,m^{-2}}$) for the periods 1850–1957 and 1958–1989. Assumed gas abundances for the three times (1850, 1958, 1989) dividing the two intervals are: CO_2 (285, 315, 351 p.p.m.), CH_4 (0.8, 1.29, 1.71 p.p.m.), and N_2O (280, 289, 309 p.p.b.). Abundances for the many CFCs and references for data sources are given in ref. 15. Calculated N_2O and CFC forcings for the interval 1850–1957 are ~0.035 and 0.015 $\mathrm{W\,m^{-2}}$, respectively.

of greenhouse gases between the 1700s and 1800s, but solar variability is one of the plausible mechanisms. Is it likely that a future decrease in solar activity may cancel greenhouse warming? That tack is taken in a recent report[32] to the chief of staff of US President Bush, which contends that solar irradiance can be expected to decline early in the twenty-first century. Thus the authors argued against measures to slow down the increase in greenhouse forcing because such efforts "could turn out to be unnecessary or even harmful if a substantial natural cooling occurs in the twenty-first century".

In comparing possible solar and greenhouse climate changes, one must take care that consistent assumptions are made about climate sensitivity. This can be done most simply by comparing the climate forcings, a simple comparison being valid because the timescales of supposed Little Ice Age forcing and recent greenhouse forcing are similar. Anthropogenic greenhouse forcing has already reached 2–2.5 $W m^{-2}$, equivalent to an increase of solar irradiance by ~1%. Given the increase of greenhouse forcing in the past three decades (Fig. 2), it is apparent that it will reach a level equivalent to a solar change of at least 2% by the middle of next century, unless the rate of growth of greenhouse-gas emissions is reduced.

The possibility of a decline of solar irradiance by 2%, although 20 times larger than the changes measured in the past 11 years, has not been ruled out categorically. The irradiance of some solar-type stars has been observed to change by several tenths of a per cent[33]. The Smithsonian Observatory monitored the Sun from mountain tops for the period 1902–1962, initially reporting variations of >1%. But comprehensive reviews of these data[34] concluded that the variations were due primarily to fluctuations of atmospheric transparency, and that they established only an upper limit of ~0.3% for solar variations. Evidence of solar change over a longer period is provided by measurements of the solar diameter. The diameter of the Sun is affected by thermal energy storage in its outer layers because it must maintain global hydrostatic equilibrium on timescales greater than an hour. The small changes of solar diameter measured over the past 275 years are near the limit of detectability[35]. Although the exact relation between the solar diameter and luminosity is uncertain, there probably were secular luminosity variations during that period, but they did not exceed several tenths of a per cent[31,36,37].

These results do not imply that solar variability has been unimportant in past climate change or that the Sun's effects will be negligible in the future. For example, it has been shown that an increase of solar irradiance by only ~0.3–0.4%, just within the range of possibility, is one conceivable explanation of the observed global warmth of the 1930 and 1940s[5]. Also, Wigley and Kelly[31] have shown that solar variations of several tenths of a per cent may explain many of the climate variations of the past 10,000 years.

Even if there are changes in the solar irradiance in coming decades, it is far from certain whether it will increase or decrease. One commonly used indirect measure of solar activity covering thousands of years is the record of the carbon isotope ^{14}C preserved in tree rings. ^{14}C is continuously formed in the atmosphere by incoming galactic cosmic rays, which are modulated by solar activity. Spectral analyses of the ^{14}C data, when extended into the future, suggest that solar activity will be increasing during the next several decades[38,39]. Inferences from such proxy records are, however, very uncertain. It is therefore important to compare the irradiance during the upcoming 11-year solar cycle to that of the previous cycle. This will provide the first reliable evidence of the extent to which solar change may add to, or subtract from, greenhouse forcing during coming decades.

We can conclude only that solar irradiance would need to decline by ~2% to counter greenhouse climate forcing by all the anthropogenic gases that will have accumlated in the atmosphere by the middle of next century, assuming no reductions in greenhouse emisssions. Although such a solar decline is not impossible, it is much larger than existing indications of solar variability. Furthermore, solar fluctuations can be positive as well as negative. Measurements of solar irradiance during the next decade or two are crucial for detection of any long-term trends and to help sort out cause and effect of observed climate changes.

Aerosols

Other than greenhouse gases, the largest known global climate forcing is that due to changing atmospheric aerosols. We first discuss stratospheric aerosols, which have a high degree of natural variability and have been well measured, and then tropospheric aerosols.

Stratospheric aerosols arise mainly from volcanic eruptions. Benjamin Franklin[40] noted that volcanic aerosols reflect sunlight to space, and therefore argued that the eruption of a large volcano on Iceland may have been responsible for unusual cold in 1783–4. Many subsequent studies have found a tendency for eruptions producing a large amount of aerosols over much of the Earth, such as Tambora (1815), Krakatoa (1883) and Agung (1963), to be associated with global cooling of a few tenths of a degree Celsius for a year or two after the eruption. But, because this is only comparable to unforced global temperature fluctuations (Fig. 1), cooling cannot be identified for every large volcano.

In situ stratospheric measurements during the past few decades show that the dominant volcanic aerosols are small droplets of sulphuric acid, which form from volcanic sulphur dioxide and persist a year or more after the eruption. Assuming that the aerosols of earlier volcanoes were also sulphuric acid, estimates of atmospheric transparency can be used to calculate the volcanic aerosol climate forcing[41,42,43]. The uncertainty in the resulting decadal-mean aerosol forcing is probably less that a factor of two.

The calculated volcanic climate forcing (Fig. 4) at times rivals or exceeds the greenhouse forcing, but the latter clearly dominates the long-term trend. Moreover, volcanic forcing is irregular. As discussed above, brief forcings have much less of an impact than those maintained for several decades. Thus a clustering of several volcanoes is required to have a significant impact on long-term climate. Nevertheless, it is obvious that stratospheric aerosols must be monitored to determine cause and effect of climate change during the next few decades.

Tropospheric aerosols are also an important climate forcing. In the 1970s it was speculated that increasing concentrations of anthropogenic aerosols might send the Earth into an ice age[45,46]. This speculation was probably fuelled by the fact that the Northern Hemisphere had cooled between 1940 and 1970, as well as by anecdotal information on increases of aerosols in many places. Industrialization, urban pollution, mechanized agriculture, population pressure in semiarid lands—the 'human volcano'—added noticeably to tropospheric aerosol loading. Although in certain circumstances, such as the absorbing haze in the Arctic[47,48], anthropogenic aerosols can have a warming effect, the overall direct radiative impact of man-made aerosols is clearly one of cooling[49].

In the past decade, since it was realized that global temperature was rising[5,50,51], tropospheric aerosols have received less attention than the greenhouse effect, but they have not been disproved as an important agent of climate change. Tropospheric aerosols have a global average optical depth $\tau \approx 0.1$ (ref. 52), where τ is defined by the vertical transmission of sunlight, $T = e^{-\tau}$. A 10% increase of τ yields a climate forcing of 0.2–0.3 $W m^{-2}$, (refs 49, 53), and the effect is nearly linear for feasible changes of τ. Although adequate measurements are unavailable, we estimate that anthropogenic aerosols comprise ~25% of all aerosols, on a global average, implying a climate forcing of 0.5–0.75 $W m^{-2}$. T. Anderson and R. Charlson (personal communication) argue that as much as 50% of global aerosols may be anthropogenic, implying a forcing of 1–1.5 $W m^{-2}$. In either case aerosol forcing is significant, but smaller than the greenhouse forcing of 2-2.5 $W m^{-2}$. We have argued[5] that aerosols are not a dominant global climate forcing because there is no evidence for an aerosol trend at remote locations such as Hawaii. Another argument[54] is that, despite anthropogenic aerosols being concentrated mainly in the Northern Hemisphere, temperature trends are similar in the two hemispheres, at least over the full century[50,51]. Nevertheless, the direct radiative effect of anthropogenic aerosols must counter greenhouse warming to some degree.

Because of their role as cloud condensation nuclei, a change of aerosols in the troposphere can alter the occurrence and optical properties of clouds. This aerosol effect is complicated, depending on factors such as the supersaturation spectrum of the aerosols[55], which describes the critical supersaturation at which each aerosol is activated as a condensation centre. It has been found, however, that in most situations added aerosols increase the number of active condensation nuclei and thus increase the cloud particle number density[56]. Twomey[55] therefore predicted that anthropogenic aerosols would decrease the mean cloud particle size and inhibit rainfall, and that both effects would increase cloud reflectivity.

Although evidence for such phenomena has existed for decades[57,58], dramatic reconfirmation of Twomey's expectations was obtained recently from satellite and aircraft measurements[59-61], which revealed cases of increased cloud reflectivity in trails behind ships, apparently owing to smokestack aerosols. The phenomenon was identified in shallow stratocumulus clouds under stable meteorological conditions, and was shown to involve decreased particle size[60] and decreased rainfall[61]. Qualitatively, the increased cloud reflectivity must cause a cooling, and order-of-magnitude estimates suggest that the global impact could be significant[62]. It is difficult to quantify the global significance of this climate forcing, however, because it has only been measured for extended stagnant conditions and global aerosol data are not available.

Anthropogenic aerosol/cloud climate forcing must also occur over continents, even though natural aerosol amounts are larger there. Cases of decreased cloud reflectivity have been observed in polluted industrial regions[63], but such cases seem to be the exception, not the rule. Large absorbing aerosols (such as carbonaceous ones) are common close to some sources, but the most extensive long-lived anthropogenic aerosols seem to be highly reflective sulphates formed from SO_2. Thus, in regions such as the continental United States, which has an extensive network of SO_2 sources, we can speculate about the possibility of significant aerosol or aerosol-cloud cooling. There is evidence for increased clouds over the United States[64,65], and the warming of 0.2-0.3 °C there in the past century[66,67] is less than the global warming of 0.5-0.6 °C[50,51]. This is weak circumstantial evidence, however, because the deviation of the US temperature trend from the global trend is in the range of natural variability for an area covering only 1.5% of the Earth.

We conclude that the lack of global aerosol data makes it impossible at present to determine the net anthropogenic aerosol forcing of the climate system. Observation of similar Northern and Southern Hemisphere warmings during the past century[50,51], although most anthropogenic aerosols were added in the Northern Hemisphere, is consistent with the expectation that greenhouse forcing dominates over aerosol forcing. But, as Wigley[68] has emphasized, there is sufficient observational and statistical uncertainty in the hemispheric temperature trends to mask a substantial aerosol forcing, as much as about half of the greenhouse forcing. Indeed, Durkee[69] has found evidence in satellite data of interhemispheric differences of aerosol and cloud properties, consistent with larger aerosol and aerosol-cloud effects in the Northern Hemisphere. Despite hemispheric dissimilarities in land cover and natural aerosols, such satellite data should eventually help to quantify the effect of aerosols.

Satisfactory quantitative analysis of the net climate forcing owing to anthropogenic aerosols will be difficult, because of the inhomogeneous distribution of the aerosols. It will be necessary to monitor global tropospheric aerosol properties, and carry out *in situ* case studies under a broad variety of conditions. Such data could yield the direct aerosol climate forcing, and, in conjunction with global cloud data, it could also allow evaluation of aerosol-cloud interactions.

Implications

Climate forcings. Anthropogenic greenhouse gases have increased steadily during the past century, and now cause a global climate forcing of 2-2.5 $W m^{-2}$. More than half of this forcing has been added in the past three decades. If emissions of these gases continue at the present or increased rates, greenhouse forcing will reach a level of at least 4-5 $W m^{-2}$ by the middle of next century.

Solar variability may also be an important climate forcing mechanism, but solar irradiance would need to decline by 2% to counteract greenhouse forcing of 4-5 $W m^{-2}$. There is no evidence indicating such a decrease; in fact, ground-based observations of solar irradiance and of the solar diameter suggest an upper limit of several tenths of one per cent for solar changes in the past 275 years. There remains the possibility that small solar changes trigger larger climate forcings; speculations have included the influence of changes in the flux of ultraviolet light on ozone or the effect of energetic solar particles on atmospheric ionization and thus cloud nucleation. But no evidence has been found for a significant impact of these mechanisms on global surface temperature. Given available scientific evidence, it would be foolish to base greenhouse policy on the hope that solar variability will somehow counteract greenhouse warming.

Aerosols are an important climate forcing. A clustering of large volcanic eruptions could counter greenhouse forcing for years or even decades. But at present we cannot forecast overall volcanic activity and have no basis for anticipating a systematic long-term impact of volcanoes on net climate forcing. On the other hand, anthropogenic tropospheric aerosols constitute a significant climate forcing, due to both their direct radiative effect and their influence on cloud optical properties. Clearly, the tropospheric aerosol forcing is one of cooling, but its magnitude is very uncertain. In the absence of appropriate measurements, it is difficult to quantify the extent to which it counteracts greenhouse forcing.

Are there other important global climate forcings? By considering the Earth as a planet, specifically those factors that influence absorption of solar energy and emission of thermal

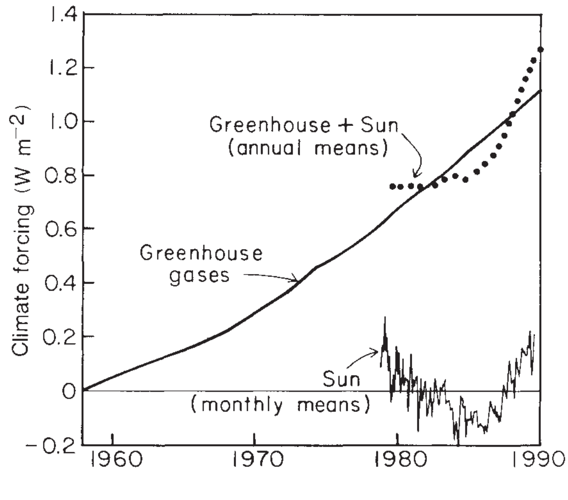

FIG. 3 Climate forcings in past three decades owing to measured changes of greenhouse gases and solar irradiance. Solar irradiance, illustrated for Nimbus 7 data[20], has been accurately measured only since 1978. Zero point of solar forcing is the 1978-1989 mean.

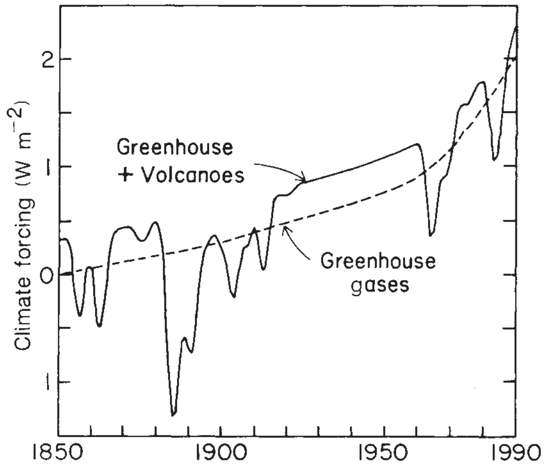

FIG. 4 Climate forcings in the past century owing to changes of greenhouse gases and stratospheric aerosols. Aerosol forcing after 1883 is based on atmospheric transmission measurements; for 1850–1883 the three largest volcanoes identified by Lamb[44] are included, with optical depth scaled relative to Agung, in proportion to the volume of ejecta. Aerosol optical depth for 1883–1960[41] is based on atmospheric transmission measurements at astronomical observatories; subsequently it is based on the transmission of sunlight through the stratosphere as recorded by approximately annual lunar eclipses[42,43]. Zero point of aerosol forcing is the 1850–1989 mean.

energy, it becomes apparent that one remaining possibility is change of reflectivity of the Earth's surface. Both deforestation and desertification tend to increase planetary reflectivity, but quantitative studies suggest that the climate impacts are confined mainly to the regions of surface change[70].

Climate response. We have so far restricted our comparisons to climate forcings thus avoiding the uncertainty about global climate sensitivity and the effect of response time. But substantial climate change must be anticipated for the forcings identified. Climate models[4–6] suggest an equilibrium global warming of 1.5–5.5 °C for doubled CO_2, which is a forcing of 4–4.5 W m^{-2}. The lower end of this range represents little net feedback, that is, it is approximately the blackbody temperature increase required to yield a flux of ~4 W m^{-2}. The upper end represents a net positive feedback of about a factor of four. This large range arises because, although feedbacks such as water vapour, sea ice and snow cover are qualitatively understood, even the direction of others such as cloud[71] and aerosol–cloud feedbacks[72], are uncertain. Recent climate model studies with alternative cloud formulations[73] reemphasize the importance of cloud feedbacks, but do not yield a climate sensitivity outside the above range. A warming of even 1.5 °C would make the Earth hotter than it has been in hundreds of thousands of years.

Lindzen[74,75] has argued that climate sensitivity may be much less than 1.5 °C for doubled CO_2. His argument, buttressed by a metaphysical presumption of a need of the planet for stability, is based primarily on the hypothesis that the net impact of increased moist convection (expected to accompany greenhouse heating) is a drying of the atmosphere, resulting in a negative water-vapour feedback. His descriptive model of moist convection includes the effect of subsidence of surrounding air, but excludes the effects of moisture detrainment at the cloud tops, cirrus anvils, large-scale dynamics and other processes. Lindzen's conclusion can be disproved on several grounds. For example, his proposed moist-convection mechanism can be tested by comparing the real atmosphere in winter and summer: at all latitudes the large-scale impact of increased summer convection is to moisten, not dry, the upper troposphere[76]. Also, satellite measurements show that even the geographical variation of the greenhouse effect[77] is in close agreement with water-vapour variations and corresponding radiative calculations, and that the maximum greenhouse effect is in regions of intense moist convection. Thus Lindzen's hypothesis of a negative water-vapour feedback cannot be reconciled with real world data, a conclusion that does not depend on uncertainties in global climate model simulations.

The best empirical measure of global climate sensitivity is provided by comparing the Earth's radiation balance in glacial and interglacial conditions. Although glacial–interglacial climate swings are associated with small changes in the Earth's orbit[78], these orbital fluctuations have little direct effect on the planetary radiation balance. Instead, the glacial–interglacial temperature differences are maintained by large changes in factors such as planetary surface reflectivity and atmospheric composition. These factors may be climate feedbacks on timescales of millennia, but on timescales of a few years or decades they are climate forcings or boundary conditions. Comparison of the glacial–interglacial global temperature change with the forcing owing to the changed boundary conditions thus provides a measure of climate sensitivity, including all fast feedback processes[8]. The last ice age, which peaked ~20,000 years ago, was 5 ± 1 °C colder than the present interglacial period, and the global climate forcing owing to changed boundary conditions (mainly changes of ice-sheet area, vegetation cover, atmospheric CO_2, CH_4 and aerosols) is estimated[8,79] to have been 7 ± 2 W m^{-2}. The inferred climate sensitivity is thus 3 °C per 4 W m^{-2} forcing. But the uncertainties in temperature and climate forcing allow a range 2–5 °C per 4 W m^{-2} forcing, a result remarkably similar to the range 1.5–5.5 °C estimated on strictly theoretical grounds. This empirical result includes not only water vapour, cloud, snow and sea-ice feedbacks, but any other feedbacks that exist in the real world, such as the aerosol–cloud feedback suggested by Shaw[80] and Charlson *et al.*[72].

One consequence of the uncertainty in climate sensitivity is an even larger uncertainty in the response time of the climate system. If climate sensitity is 1.5–2 °C for a forcing of 4 W m^{-2}, most of the warming is realized within one to two decades after the forcing is applied; but if the sensitivity is 4–5 °C, the response time may be more than a century[8,22,23]. The climate response time increases strongly with increasing climate sensitivity, more rapidly than linearly[22], because the positive climate feedbacks associated with a high sensitivity only come into play in response to the warming. Because most of the greenhouse forcing has been added very recently (Figs 2, 4), it is clear that a large part of the eventual greenhouse warming owing to anthropogenic gases already in the atmosphere has not yet occurred. This unrealized warming calls into question a 'wait and see' policy towards the greenhouse issue, because the magnitude of this climate time-bomb will grow if greenhouse-gas emissions continue to increase.

Measurements. The interest in global climate change raises the possibility of support for the measurements of climate forcings, feedbacks and diagnostic parameters, which will be needed to sort out cause and effect of climate change. The above discussion emphasizes the need for data on all significant competing factors, including solar irradiance and atmospheric aerosols.

The most precise measurements of solar irradiance recently ended as the Solar Maximum Mission was brought down by atmospheric drag; plans for the Space Shuttle to boost the Solar Maximum Mission to higher orbit were cancelled in the wake of the Challenger disaster and the resulting reduction in mission frequency. Hopefully, although the measurements are less precise, solar instruments on Nimbus 7 and Earth Radiation Budget satellites will continue to function until the planned 1992 launch of the Upper Atmospheric Research Satellite, with its active-cavity radiometer.

The difficulty of achieving adequate precision in solar-irradiance measurements is highlighted by the changes in the Nimbus 7 data that occur when corrections are made for small errors in the assumed instrument pointing[11]. The precision needed to reveal decadal trends in the solar irradiance can be provided by instruments whose sensors are internally monitored for degradation of sensitivity, as was the case for the instrument of the Solar Maximum Mission, provided there is temporal overlap of successive instruments. Because the time of failure of an instrument or satellite is not generally predictable, and because the instruments are not extremely expensive, the approach should be to have two solar instruments simultaneously in orbit, thus providing a valuable cross-check as well as continuity of calibration.

Measurements of changes of the solar diameter with the accuracy achievable from space are also important. In conjunction with the irradiance data, these will serve to clarify the relation of diameter and luminosity, and perhaps aid eventual predicatability of long-term solar changes.

Aerosols are the source of our greatest uncertainty about climate forcing. Tropospheric aerosols are difficult to monitor because of their spatial inhomogeneity, but they are a crucial variable because of the strong anthropogenic influence on their amount. Not only will it be necessary to monitor the aerosols, but also to have continued global cloud observations, because of possible interactions between aerosols and clouds.

The concept of a 'mission to planet Earth', involving satellites from the United States, Europe and Japan, is presently undergoing intense study and early development. Although intended to cover many aspects of global change, this project has potential for important contributions to the understanding of climate change, provided care is taken that it does not displace resources from other high-priority climate research and monitoring. In planning these activities it is important to recognize that a crucial requirement for climate data sets is long-term continuity. Related to this is the fact that many data sets are best obtained from a variety of conventional sources: operational weather satellites, ships, the world weather network, ground-based and aircraft special studies, and low-cost small-satellite missions. A new initiative could provide a great service by providing resources for analysis of presently available data, and by identifying and filling key gaps in the data.

Policy. In view of the enormous economic and social implications of climate change, researchers must communicate with policy makers, and, indeed, some useful advice can now be given. Based on the complexity of the scientific issues about climate forcings (such as tropospheric aerosols), climate feedbacks (such as clouds) and climate response time (such as ocean mixing and heat storage) it is clear that, contrary to recent advice delivered to the US administration[32], the scientific issues will not be settled in 3-5 years. Also, bigger computers, by themselves, will contribute little to our understanding of these problems. What is needed most is support for research using existing data, continuation and improvement of observations, and, perhaps most of all, training of people to define and analyse future data.

Nor can researchers presently provide a prescription for how the world could achieve climate stabilization, should policy-makers decide that such a goal is desirable. This is illustrated by a *gedanken* (thought) experiment concerning the rate of the use of fossil fuel. The burning of fossil fuel releases CO_2, causing about half of the anthropogenic greenhouse effect, but it also releases SO_2, forming atmospheric aerosols which partially counter greenhouse warming by reflecting sunlight and increasing cloud cover. The lifetime of added CO_2 is of the order of 10^2 years (although it cycles through the biosphere more rapidly) whereas the lifetime of sulphate aerosols is only a few days. This difference in lifetimes has important implications for the effectiveness of changes in fossil-fuel use.

First, as an extreme labelled Case I, we assume that tropospheric aerosols generated by fossil fuels have cancelled a large fraction of the anthropogenic greenhouse effect, say about half, which is approximately the amount of the greenhouse effect owing to CO_2. Case I is conceivable, because observed warming could have been caused by the other greenhouse gases. In Case I, if fossil-fuel use were stabilized (or reduced) warming would accelerate, because the short-lived anthropogenic aerosols would stabilize (or decrease) but CO_2 would continue to increase. CO_2-induced warming is eliminated in Case I only by continued exponential increase of fossil-fuel use. But that would be a Faustian bargain, because fossil fuels would run out, whereupon a huge CO_2-induced warming would begin.

As Case II, we assume that aerosol cooling is negligible compared to CO_2-induced warming. In that case, any reduction in the use of fossil fuel reduces the growth of CO_2 warming in a straightforward way. The real world almost certainly lies somewhere in the continuum between Cases I and II, but we do not know where. Thus, until the research on aerosols is carried out (a difficult task), we do not even know the direction of the change of climate forcing on decadal timescales which would be caused by a modification of fossil-fuel use.

In the presence of such uncertainties, can any useful advice be given to policy makers? We believe so. It is clearly desirable to reduce the ultimate magnitude of the 'experiment' that man is carrying out on the Earth, and there are many actions that could accomplish that and which make good sense on other grounds. These include phasing out CFCs, improving energy efficiency, increasing recycling, reducing deforestation and planting trees in appropriate places. All of these are needed for other reasons, and, in the long-term, pay for themselves. It will, however, require unprecedented international cooperation to achieve a turnaround of global greenhouse-gas emissions. The Montreal Protocol, motivated by a common desire to protect the stratospheric ozone layer, promises significant progress on CFC reductions. The first steps of an analogous process for climate protection are being taken by the Intergovernmental Panel on Climate Change, but it is difficult to predict its prospects for success.

Finally, we would be remiss if, in discussing the policy implications of anthropogenic climate change, we did not raise the issues of alternative energy sources and global population. It seems imperative that governments give much higher priority to research and development on energy sources that produce little or no greenhouse gases. Otherwise we risk the danger of soon finding ourselves, in the mid-American vernacular, up the proverbial creek without a paddle. Also, it is obvious that even sizable reduction of *per capita* greenhouse-gas emissions will be negated if global population continues to increase at the present rate. Thus governments must foster conditions leading to population stabilization, if we are to preserve the global climate and environment. □

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ARTICLES

Stimulation of p21^{ras} upon T-cell activation

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External signals that control the activity of proteins encoded by the *ras* proto-oncogenes have not previously been characterized. It is now shown that stimulation of the antigen receptor of T lymphocytes causes a rapid activation of p21^{ras}. The mechanism seems to involve a decrease in the activity of GAP, the GTPase-activating protein, on stimulation of protein kinase C. In lymphocytes, p21^{ras} may therefore be an important mediator of the action of protein kinase C.

THE activated *ras* oncogenes (Ha-, Ki- and N-*ras*) can transform mammalian cells in culture and have been implicated in the formation of a high proportion of human tumours[1]. The *ras* oncogenes encode closely related proteins of relative molecular mass 21,000 (p21^{ras}) that bind GTP and catalyse its hydrolysis to GDP. Ras proteins can stimulate cellular growth and other events when they are bound to GTP ('active') but not when they are bound to GDP ('inactive')[2–4]. Mutations that allow p21^{ras} to transform cells all cause accumulation of the GTP-bound form of the protein; many inhibit the intrinsic GTPase activity of p21^{ras} (ref. 5) and others increase the rate of exchange of bound nucleotide with cytoplasmic pools, which contain much more GTP than GDP[6].

No cellular stimulus has previously been identified that controls the activation state of mammalian p21^{ras}, as measured by the amount of GTP bound to it relative to GDP. But a likely component of the *ras* pathway has been identified in GAP, a protein that stimulates the hydroloysis of GTP on p21^{ras}, thereby causing it to enter the inactive GDP-bound state[7]. Ways in which the activity of GAP might be regulated remain the subject of speculation.

Here we report that p21^{ras} is indeed part of a signal transduction pathway and that in T lymphocytes its activation state can be rapidly regulated by an extracellular stimulus operating on a cell-surface receptor.

Stimulation of p21^{ras}

The activation state of p21^{ras} was measured in intact T cells by metabolic labelling with [^{32}P]orthophosphate and then lysing them and immunoprecipitating p21^{ras}. Figure 1*a* is an autoradiogram showing the nucleotides bound to the endogenous p21^{ras} in human peripheral blood lymphoblasts (PBLs)[8] and in the human T-cell line Jurkat[9]. Although p21^{ras} from untreated cells is almost entirely GDP-bound, on treatment with the T-cell-activating lectin phytohaemagglutinin (PHA)[10] or CD3-specific monoclonal antibody UCHT-1 (ref. 11), a large amount of GTP accumulates on p21^{ras}. In the cell line HPB-ALL, where the antigen receptor is uncoupled from phosphatidyl inositol (PtdIns) turnover[12], reagents specific for the antigen receptor fail to influence the nucleotide bound to p21^{ras} (Fig.